Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews
12 (2008) 1221–1250
RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS
www.elsevier.com/locate/rser

Energy storage systems—Characteristics and comparisons

H. Ibrahim[a,b,*], A. Ilinca[a], J. Perron[b]

[a]*Wind Energy Research Laboratory (WERL), Université du Québec à Rimouski, 300 allée des Ursulines, Qué. Canada G5L 3A1*
[b]*Anti Icing Materials International Laboratory (AMIL), Université du Québec à Chicoutimi, 555 boulevard de l'Université, Qué. Canada G7H 2B1*

Received 1 December 2006; accepted 5 January 2007

Abstract

Electricity generated from renewable sources, which has shown remarkable growth worldwide, can rarely provide immediate response to demand as these sources do not deliver a regular supply easily adjustable to consumption needs. Thus, the growth of this decentralized production means greater network load stability problems and requires energy storage, generally using lead batteries, as a potential solution. However, lead batteries cannot withstand high cycling rates, nor can they store large amounts of energy in a small volume. That is why other types of storage technologies are being developed and implemented. This has led to the emergence of storage as a crucial element in the management of energy from renewable sources, allowing energy to be released into the grid during peak hours when it is more valuable.

The work described in this paper highlights the need to store energy in order to strengthen power networks and maintain load levels. There are various types of storage methods, some of which are already in use, while others are still in development. We have taken a look at the main characteristics of the different electricity storage techniques and their field of application (permanent or portable, long- or short-term storage, maximum power required, etc.). These characteristics will serve to make comparisons in order to determine the most appropriate technique for each type of application.

Keywords: Renewable energy; Storage; Compressed air; Batteries; Flywheel; Fuel cells; Energy efficiency; Environmental impact; Effectiveness; Costs

*Corresponding author. Tel.: +1 418 7231986x1285; fax: +1 418 7241879.
E-mail address: hussein.ibrahim@uqar.qc.ca (H. Ibrahim).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2007.01.023

Contents

1. Introduction

Electrical energy is an invisible, omnipresent commodity that is readily available at the lowest possible cost in most cases. It has long been considered a common consumer good [1]. Today, it makes up 12% of the total energy processed by humanity, a proportion that is expected to grow over the next few years (34% predicted for 2025) in a context of diminishing fossil fuels, growing use of renewable energy, and greater respect for the environment [2].

At present, the production of electricity is highly centralized and, often, a long distance away from its end users. Load levelling is initially based on the prediction of daily and seasonal needs, but also, when production is not sufficient, on the contribution of secondary modes like hydraulic and thermal plants. In fact, these plants also use stored energy: water for the pumped storage plants, and fossil fuels for the thermal plants.

Delocalized electricity production and the introduction of variable, fluctuating sources (renewable energy: solar, wind turbines, etc.) increase the difficulty of stabilizing the power network, mainly due to a supply–demand imbalance. It is therefore convenient to generate the energy, transmit it, convert it, and then store it if need be. More than ever then, the storage of electrical energy has become a necessity. But electricity is difficult to store as this requires bulky, costly equipment.

It may be useful to keep in mind that centralized production of electricity has led to the development of a complex system of energy production–transmission, making little use of storage (today, the storage capacity worldwide is the equivalent of about 90 GW [3] of a total production of 3400 GW, or roughly 2.6%). In the pre-1980 energy context, conversion methods for the "storage of alternate current" were extremely costly, unreliable, or simply were not being used. This, along with the fact that electricity is mass produced, transmitted, and used in AC, has led to the belief that electricity cannot be stored. However, high-performance, inexpensive power electronics able to handle very high power levels have changed all that. It can now be asserted that electricity can be stored, even if it is indirect storage. But this requires that investment and operating costs be kept to an acceptable level, and that the environmental issues be considered.

2. Storage and renewable energy

The development and use of renewable energy has experienced rapid growth over the past few years. In the next 20–30 years all sustainable energy systems will have to be based on the rational use of traditional resources and greater use of renewable energy.

Decentralized electrical production from renewable energy sources yields a more assured supply for consumers with fewer environmental hazards. However, the unpredictable character of these sources requires that network provisioning and usage regulations be established for optimal system operation.

Renewable resources have a major inconvenient: they fluctuate independently from demand. Yet they are plentiful and conversion systems are becoming more and more affordable. Their significant contribution to sustainable energy use will however require considerable further development of storage methods. This will open up a new field of application, especially due to the growth of electrical production from renewable energy, along with decentralized production.

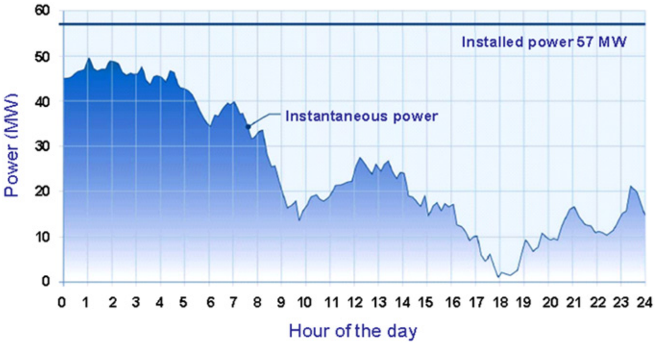


Fig. 1. Fluctuation of instantaneous power on March 16, 2004, at the Cap-Chat (Quebec, Canada) wind farm (76 turbines) [4].

Wind energy is the current "star" in the field of renewable energy for electrical production. Still, the power generated by wind turbines over time is characteristically uneven due to the unpredictable nature of their primary source of power (Fig. 1). This only increases the problems inherent to the integration of a great number of wind turbines into power networks, making their contribution rather difficult to manage (regulating voltage and frequency, wind-farm operation, etc.). Yet, the stability of a network rests on the equilibrium between supply and demand. Increasing the integration rate of wind turbines will therefore be a function of the ability to regulate supply, which electrical energy storage systems should solve.

3. Technical and economical advantages of energy storage

The main economical advantages that make the electricity storage an interesting venture could be described as follows.

3.1. Energy transfer

The intermediary energy obtained from electricity, through the transformation of a very-low-cost primary energy source utilized in regular power plants, will be stored and utilized at an appropriate time as a substitute for the expensive primary power used in peak-load power stations, or for the "virtual energy" represented by fines that can be levied as a result of a breakdown in supply. There are two modes of energy production for which storage is clearly important:

- Conventional energy production, the storage of which could compensate for a temporary loss of production of a generating unit and fulfill a commercial obligation of pre-sold energy supply, and thus avoid penalties. The power level is comparable to that stipulated and the quantity of stored energy should be a compromise between the desirable duration of backup power and the potential penalties.
- Renewable energy production, the storage of which adds value to the supplied current by making this type of energy predictable (e.g., the delivery of electrical power during peak hours). However, the cost of buffer storage should be considered. The stored

power could only satisfy a portion of the nominal production capacity, while the energy should be made available as a result of a contractual compromise.

3.2. Network savings

Schematically, power networks are comprised of many generating units, various levels of transmission and distribution lines and associated stations and substations, and a great many consumers with wide-ranging power requirements.

Power consumption by users, during the day, is characterized by disparity and fluctuation, meaning that minimum consumption is nearly half of a maximum peak (Fig. 2). End-user demand, in terms of ratio between peak and average power levels, often reaches a value of 10. This leads to the over-dimensioning of production and transmission equipment, which are designed as a function of peaks in demand rather than average daily consumption.

However, load levelling helps to reduce fluctuations to a minimum, making the supply more predictable. Consequently, this would make it possible to use the existing transmission and distribution facilities for many years to come.

Moreover, the levelling of consumption at the final distribution level would help both to reduce the power installed and to get the most out of the existing network. But it is important to note that, despite statistical levelling, the power demand varies considerably as a function of the time of day or from season to season. That is where the importance of storage comes to bear; a local supply compensating for load variations would make it possible to operate transmission, subtransmission, and distribution networks with lighter designs.

3.3. The kinetic advantage

The flexibility of future storage and retrieval systems can help provide instant response to demand and, as a consequence, add flexibility to the network in terms of load levelling. Network imbalance can be caused by a temporary production deficit, which could possibly be predicted. The need could also be the result of production failures. That is why the resulting gains due to storage systems need to secure a return on the costs of the following double-conversion chain: Electricity ⇒ Storable intermediary energy ⇒ Electricity.

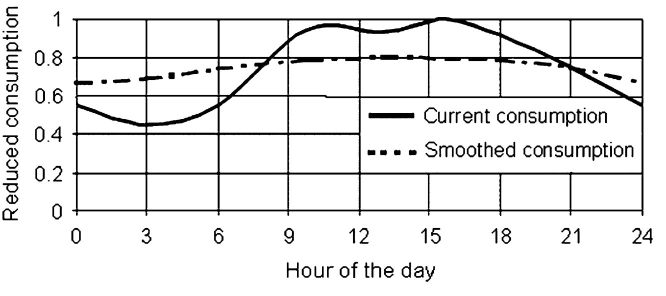


Fig. 2. Average daily power consumption in France [1].

4. Electricity storage systems

Electricity storage can be achieved effectively. Initially, it must be transformed into another form of storable energy and to be transformed back when needed.

There are many possible techniques for energy storage, found in practically all forms of energy: mechanical, chemical, and thermal. These have all been explored, leading to the birth of the techniques that will be described herein. The storage technologies that answer to specific technical and economic criteria, which vary considerably as a function of the applications and needs, will obviously be of different types. The technologies are many, but a comparative study is rendered difficult by the fact that, among others, their levels of development vary greatly [5].

The storage techniques can be divided into four categories, according to their applications:

1. Low-power application in isolated areas, essentially to feed transducers and emergency terminals.
2. Medium-power application in isolated areas (individual electrical systems, town supply).
3. Network connection application with peak leveling.
4. Power-quality control applications.

The first two categories are for small-scale systems where the energy could be stored as kinetic energy (flywheel), chemical energy, compressed air, hydrogen (fuel cells), or in supercapacitors or superconductors.

Categories three and four are for large-scale systems where the energy could be stored as gravitational energy (hydraulic systems), thermal energy (sensible, latent), chemical energy (accumulators, flow batteries), or compressed air (or coupled with liquid or natural gas storage).

4.1. Pumped hydro storage (PHS)

The main advantage of this technology is that it is readily available. It uses the power of water, a highly concentrated renewable energy source. This technology is currently the most used for high-power applications (a few tens of GWh or 100 of MW).

Pumped storage subtransmission stations will be essential for the storage of electrical energy. The principle is generally well known: during periods when demand is low, these stations use electricity to pump the water from the lower reservoir to the upper reservoir (Fig. 3). When demand is very high, the water flows out of the upper reservoir and activates the turbines to generate high-value electricity for peak hours.

Pumped hydroelectric systems have a conversion efficiency, from the point of view of a power network, of about 65–80%, depending on equipment characteristics [6]. Considering the cycle efficiency, 4 kWh are needed to generate three. The storage capacity depends on two parameters: the height of the waterfall and the volume of water (Fig. 4). A mass of 1 ton falling 100 m generates 0.272 kWh. The main shortcoming of this technology is the need for a site with different water elevations.

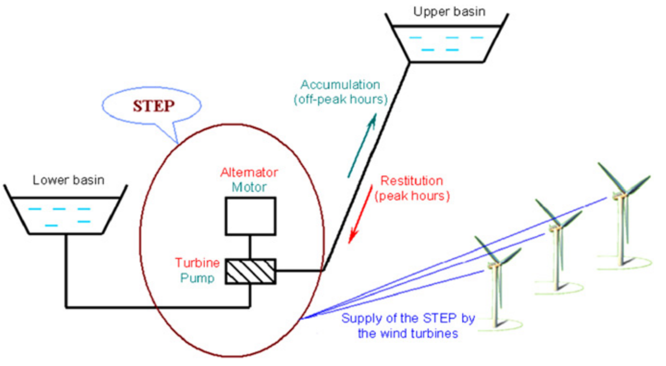


Fig. 3. Illustration of pumped hydro storage with the pumping energy supplied by wind turbines [7].

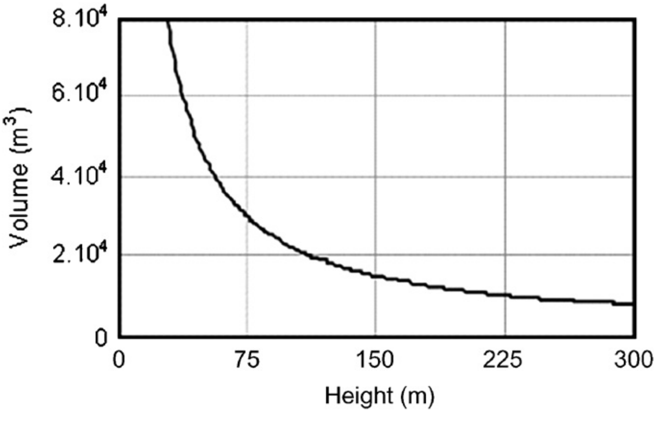


Fig. 4. Water volume needed at a given height to store 6 MWh [1].

4.2. Thermal energy storage (TES)

There are two types of TES systems, depending on whether they use sensible or latent heat.

Latent-fusion-heat TES makes use of the liquid–solid transition of a material at constant temperature. During accumulation, the bulk material will shift from the solid state to liquid and, during retrieval, will transfer back to solid. The heat transfers between the thermal accumulator and the exterior environment are made through a heat-transfer fluid. The energy is stored at a given temperature, the higher the heat the higher the concentration; the fusion enthalpy grows with the fusion temperature of the bulk material used.

Despite its highly corrosive nature, sodium hydroxide is considered to be a good storage fluid. It has a high fusion temperature, an adequate thermal conductivity coefficient, high-temperature stability, and a very low steam pressure. Between 120 and 360 °C, it has a specific thermal storage capacity (mass or volume) of 744 MJ/t, or 1332 MJ/m^3 [8].

Setting up a sodium-hydroxide, latent-heat accumulation systems in electric boilers could help limit demand for electrical power in industrial processes where the needs for steam are not continuous and vary in intensity.

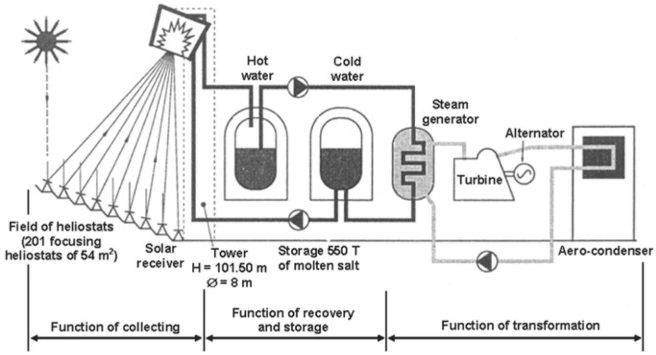


Fig. 5. Illustration of the Thémis station in France [8].

Sensible heat thermal storage is achieved by heating a bulk material (sodium, molten salt, pressurized water, etc.) that does not change states during the accumulation phase; the heat is then recovered to produce water vapor, which drives a turbo-alternator system.

The use of molten salt in the Thémis station in France has made it possible to store heat economically and simplify the regulation of the solar panel (Fig. 5) [8]. This system was designed to store 40,000 kWh of thermal energy, equivalent to almost 1 day of average sunlight, in 550 tonnes of fused electrolyte [8].

Using water as storage fluid involves high temperatures, above 200 °C, making it impossible to store the water is a confined groundwater basin because irreparable damage to the ground would ensue. Very large volume watertight cisterns set in rock are needed [8].

During off-peak hours, the hot water for storage can be obtained from a thermal plant, for example, condensation of the high-pressure steam from the boiler (Fig. 6), or by tapping, at lower temperature, from the turbine outlets. Generating extra electricity during peak hours can be achieved by heating the water supply when retrieving stored energy and simultaneously reducing turbine outlet. A 5% overpower is obtained by an increase in steam output through the turbine.

A new technology that has unfortunately not yet been applied is high-temperature, sensible heat storage with turbine (Fig. 7). It consists in heating a refractory material to 1400 °C by electric resistances (high efficiency) during storage and retrieving the accumulated energy by injecting the air heated by the refractory material into a combined-cycle turbine [9]. The estimated efficiency of such a system is in the area of 60%. The system can store very large quantities of energy without major hazards and is not subject to geological constraints. Losses due to self-discharge are relatively small, especially for very large systems. For example [6], a thermal storage reservoir designed for 1000 kWh, would only be 20 m in diameter and 20 m high, for a volume of 5000 m^3. The estimated investment costs are considered to be among the lowest, a good reason why this concept should be developed.

4.3. Compressed air energy storage (CAES)

CAES relies on relatively mature technology with several high-power projects in place.

A power plant with a standard gas turbine uses nearly two-thirds of the available power to compress the combustion air. It therefore seems possible, by separating the processes in

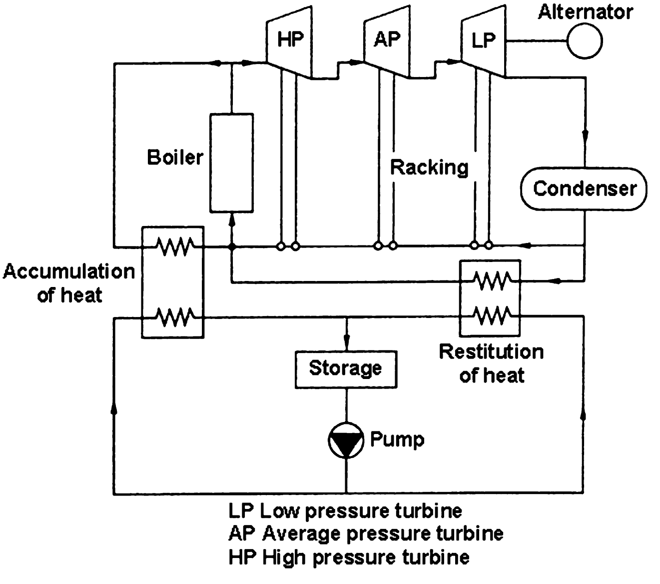


Fig. 6. Sensible heat storage of electricity in a power plant [8].

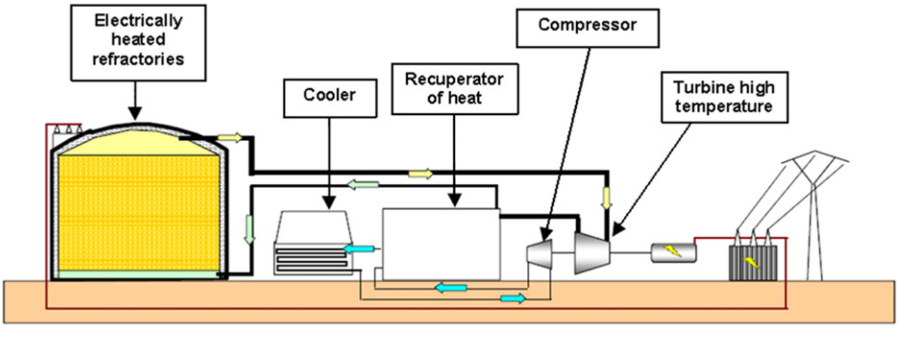


Fig. 7. High-temperature heat storage with turbine [6].

time, to use electrical power during off-peak hours (storage hours) in order to compress the air, and then to produce, during peak hours (retrieval hours), three times the power for the same fuel consumption by expanding the air in a combustion chamber before feeding it into the turbines. Residual heat from the smoke is recovered and used to heat the air (Fig. 8).

Compressed air energy storage is achieved at high pressures (40–70 bars), at near-ambient temperatures. This means less volume and a smaller storage reservoir. Large caverns made of high-quality rock deep in the ground, ancient salt mines, or underground natural gas storage caves are the best options for compressed air storage, as they benefit from geostatic pressure, which facilitates the containment of the air mass (Fig. 9). A large number of studies [11] have shown that the air could be compressed and stored in underground, highpressure piping (20–100 bars). This method would eliminate the geological criteria and make the system easier to operate (Fig. 10).

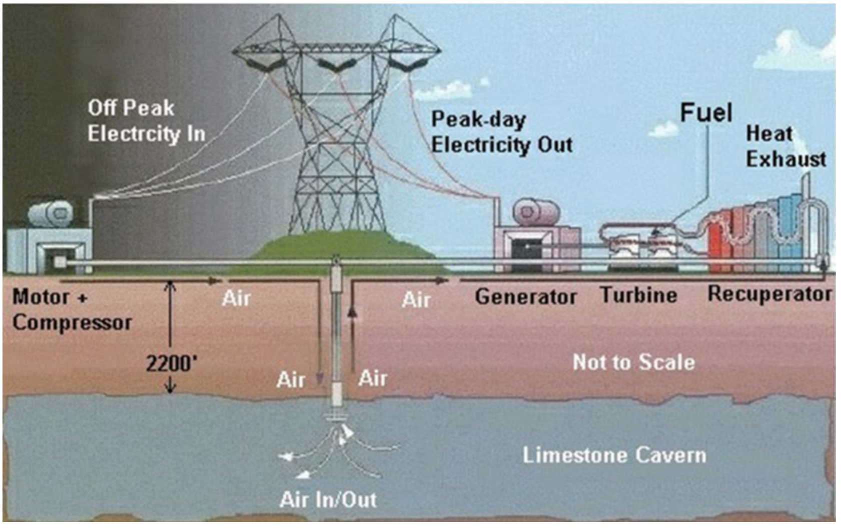


Fig. 8. Illustration of compressed-air energy storage [10].

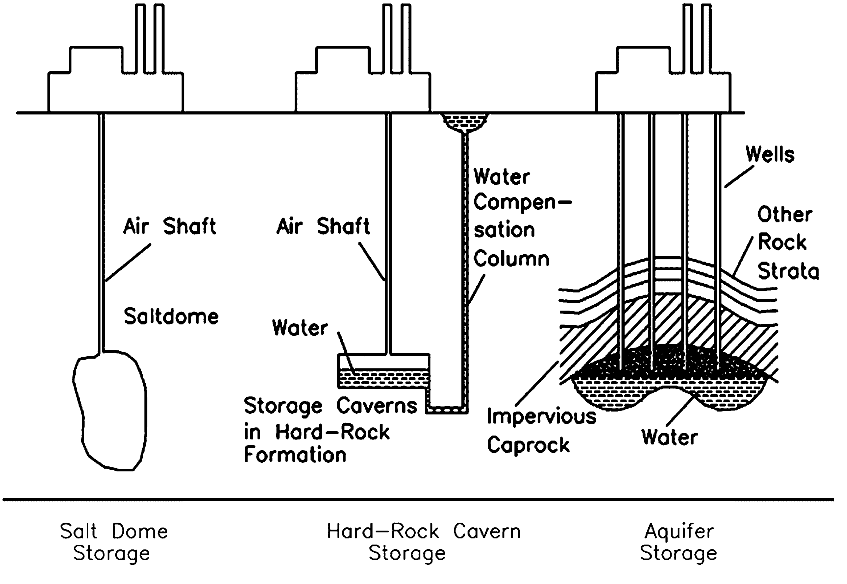


Fig. 9. Different types of compressed air storage reservoirs [11].

The energy density for this type of system is in the order of 12 kWh/m^3 [6], while the estimated efficiency is around 70% [12]. Let us note that to release 1 kWh into the network, 0.7–0.8 kWh of electricity needs to be absorbed during off-peak hours to compress the air, as well as 1.22 kWh of natural gas during peak hours (retrieval). To improve efficiency and reduce operation costs, air leaks (self-discharge) must be kept to an absolute minimum.

The first storage station using an underground compressed air reservoir has been in operation since November 1978 in Huntorf, near Bremen, Germany [8]. In 1991, an

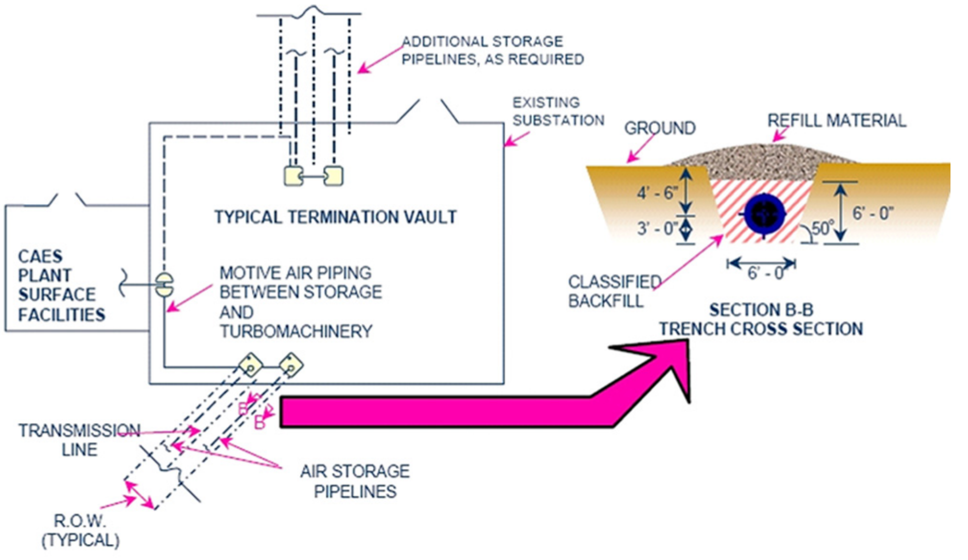


Fig. 10. Illustration of underground compressed air storage piping [11].

American installation in MacIntosh, Alabama, began to deliver 100 MW of power for 226 h. The ambient air is compressed and stored at a pressure between 40 and 70 bars in a 2,555,000-m^3 cavern, 700 m deep in the ground [13]. During summer, the system generates energy 10 h per day on weekdays. The company using this application partially recharges the cavern weekday nights and full recharge is done on weekends. The system is in use 1770 h per year [13].

4.4. Small-scale compressed air energy storage (SSCAES)

Compressed air storage under high pressure in cylinders (up to 300 bars with carbon-fibre structures) is a good solution for small- and medium-scale applications. Using an electric compressor that can be turned into a generator during retrieval, the system has an overall efficiency of 50%. It is a function of the recharging and discharging power. The number of cycles is in the order of a few tens of thousands as it is mainly limited by the mechanical fatigue of the cylinders. This type of installation has been proposed in the United States as temporary network support (Small Scale Compressed Air Energy Storage: SSCAES) [6].

4.5. Energy storage coupled with natural gas storage (NGS)

The idea is to couple underground natural gas storage with electricity storage. The pressure difference between high-pressure gas storage ($\approx$200 bars) in reservoirs deep underground (1500 m) and gas injected into the conduits with a maximum service pressure of 60–80 bars leads to the consumption of energy for compression, energy that could be released in the form of electricity during decompression [6].

The liquefaction of natural gas or compressed air requires a large amount of energy. Existing Japanese technology looks to use the resulting heat exchanges to store electricity [6]. The idea is to use two storage reservoirs for liquefied natural gas and liquid air, regenerative heat exchangers, a compressor, and a gas turbine. During the burning of natural gas to activate the turbine and generate electricity, the liquid air and the gas are vaporized and the cold thus created is conserved in the exchangers. During off-peak hours, the air is cooled by the already-stored air, compressed with an electric compressor, and is finally liquefied and stored.

4.6. Energy storage using flow batteries (FBES)

Flow batteries are a two-electrolyte system in which the chemical compounds used for energy storage are in liquid state, in solution with the electrolyte. They overcome the limitations of standard electrochemical accumulators (lead–acid or nickel–cadmium for example) in which the electrochemical reactions create solid compounds that are stored directly on the electrodes on which they form. This is therefore a limited-mass system, which obviously limits the capacity of standard batteries.

Various types of electrolyte have been developed using bromine as a central element: with zinc (ZnBr), sodium (NaBr), vanadium (VBr) and, more recently, sodium polysulfide. The electrochemical reaction through a membrane in the cell can be reversed (charge–discharge). By using large reservoirs and coupling a large number of cells, large quantities of energy can be stored and then released by pumping electrolyte into the reservoirs (see Fig. 11).

The best example of flow battery was developed in 2003 by Regenesys Technologies, England, with a storage capacity of 15 MW–120 MWh. It has since been upgraded to an electrochemical system based entirely on vanadium. The overall electricity storage efficiency is about 75% [5].

4.7. Fuel cells—Hydrogen energy storage (FC– HES)

Fuel cells are a means of restoring spent energy to produce hydrogen through water electrolysis. The storage system proposed includes three key components: electrolysis which consumes off-peak electricity to produce hydrogen, the fuel cell which uses that hydrogen and oxygen from air to generate peak-hour electricity, and a hydrogen buffer tank to ensure adequate resources in periods of need.

Oxidation-reduction between hydrogen and oxygen is a particularly simple reaction which occurs within a structure (elementary electrochemical cell) made up of two electrodes (anode–cathode) separated by electrolyte, a medium for the transfer of charge as ions (Fig. 12).

There are many types of fuel cells, such as: Alkaline Fuel Cell (AFC), Polymer Exchange Membrane Fuel Cell (PEMFC), Direct Methanol Fuel Cell (DMFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC). The basic differences between these types of batteries are the electrolyte used, their operating temperature, their design, and their field of application. Moreover, each type has specific fuel requirements.

Fuel cells can be used in decentralized production (particularly low-power stations—residential, emergency, etc.), spontaneous supply related or not to the network, mid-power

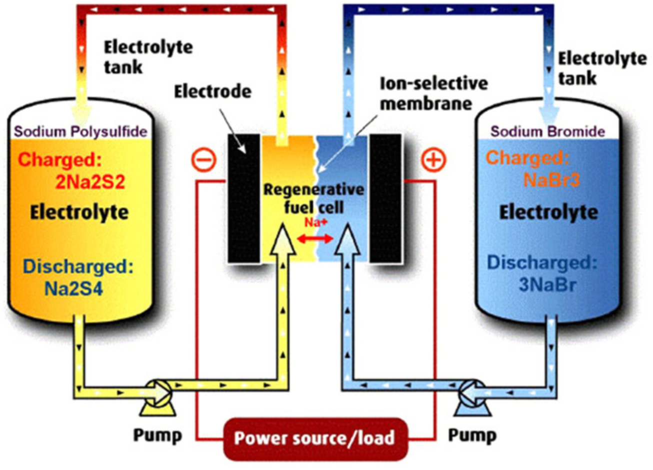


Fig. 11. Illustration of a flowbattery of type PSB (Polysulfide Bromide Battery) [10].

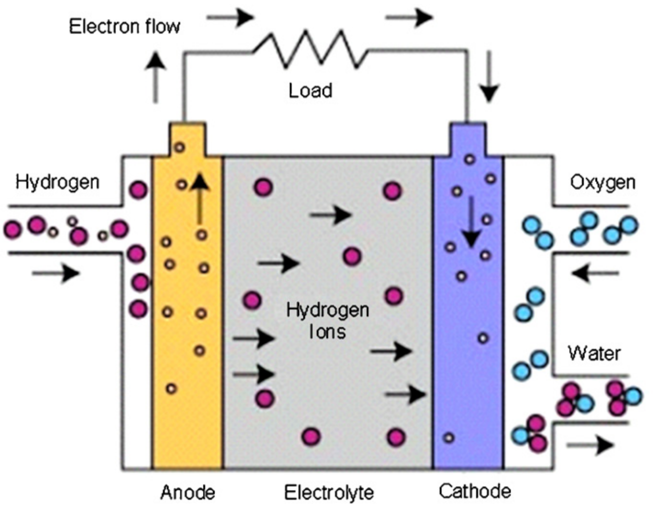


Fig. 12. Illustration of a fuel cell.

cogeneration (a few 100 kW), and centralized electricity production without heat upgrading. They can also represent a solution for isolated areas where the installation of power lines is too difficult or expensive (mountain locations, etc.).

There are several hydrogen storage modes, such as: compressed, liquefied, metal hydride, etc. For station applications, pressurized tanks with a volume anywhere between 10^{-2} and 10,000 m^3 are the simplest solution to date. Currently available commercial cylinders can stand pressures up to 350 bars.

Combining an electrolyzer and a fuel cell for electrical energy storage is a low-efficiency solution (at best 70% for the electrolyzer and 50% for the fuel cell, and 35% for the

combination). As well, the investment costs are prohibitive and life expectancy is very limited, especially for power network applications.

4.8. Chemical storage

Chemical storage is achieved through accumulators. These systems have the double function of storage and release of electricity by alternating the charge–discharge phases. They can transform chemical energy generated by electrochemical reactions into electrical energy and vice versa, without harmful emissions or noise, and require little maintenance.

There is a wide range of technologies used in the fabrication of accumulators (lead–acid, nickel–cadmium, nickel–metal hydride, nickel–iron, zinc–air, iron–air, sodium–sulphur, lithium–ion, lithium–polymer, etc.) and their main assets are their energy densities (up to 150 and 2000 Wh/kg for lithium) and technological maturity (Fig. 13). Their main inconvenient however is their relatively low durability for large-amplitude cycling (a few 100 to a few 1000 cycles). They are often used in portable systems, but also in permanent applications (emergency network back-up, renewable-energy storage in isolated areas, etc.).

The minimum discharge period of the electrochemical accumulators rarely reaches below 15 min. However, for some applications, power up to 100 W/kg, even a few kW/kg, can be reached within a few seconds or minutes. As opposed to capacitors, their voltage remains stable as a function of charge level. Nevertheless, between a high-power recharging operation at near-maximum charge level and its opposite, that is to say a power discharge nearing full discharge, voltage can easily vary by a ratio of two.

4.9. Flywheel energy storage (FES)

Flywheel energy accumulators are comprised of a massive or composite flywheel coupled with a motorgenerator and special brackets (often magnetic), set inside a housing at very

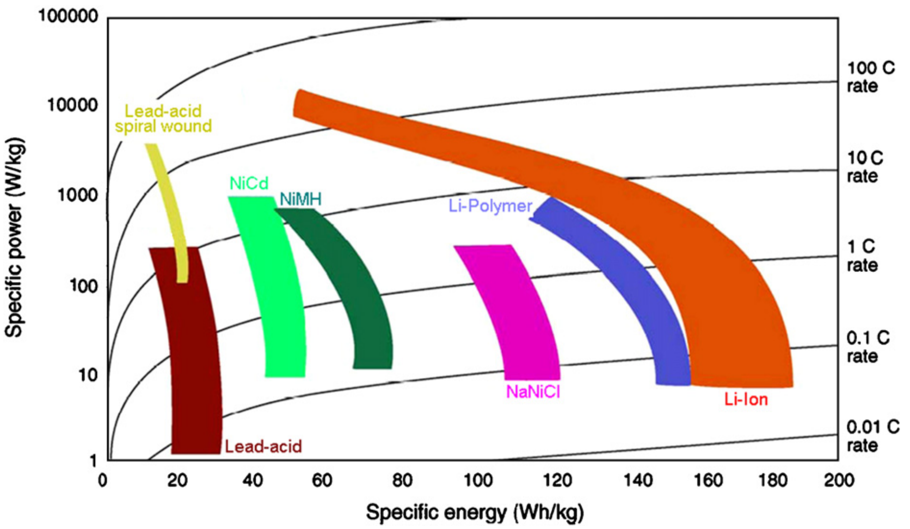


Fig. 13. Distribution of the different electrochemical accumulators according to their energy densities, their power [14].

low pressure to reduce selfdischarge losses (Fig. 14) [9]. They have a great cycling capacity (a few 10,000 to a few 100,000 cycles) determined by fatigue design.

To store energy in an electrical power system, high-capacity flywheels are needed. Friction losses of a 200-tons flywheel are estimated at about 200 kW. Using this hypothesis and instantaneous efficiency of 85%, the overall efficiency would drop to 78% after 5 h, and 45% after one day. Long-term storage with this type of apparatus is therefore not foreseeable.

From a practical point of view, electromechanical batteries are more useful for the production of energy in isolated areas. For example, some systems have been installed to supply areas of scattered houses, as well as the islands of Scotland and Wales [15]. In the first case, the batteries are used essentially to regulate and increase the quality of the current (constant and continuous voltage). Where supplying the islands is concerned, electromechanical batteries are used to ensure that a maximum of the energy consumed is generated by the local wind farms, and to improve the quality of supply when wind-turbine production is on the threshold of demand.

Kinetic energy storage could also be used for the distribution of electricity in urban areas through large capacity buffer batteries, comparable to water reservoirs, aiming to maximize the efficiency of the production units. For example, large installations made up of forty 25 kW–25 kWh systems are capable of storing 1 MW that can be released within 1 h.

4.10. Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage is achieved by inducing DC current into a coil made of superconducting cables of nearly zero resistance, generally made of niobium-titane (NbTi) filaments that operate at very low temperature (−270 °C). The current increases when charging and decreases during discharge and has to be converted for AC or DC voltage applications.

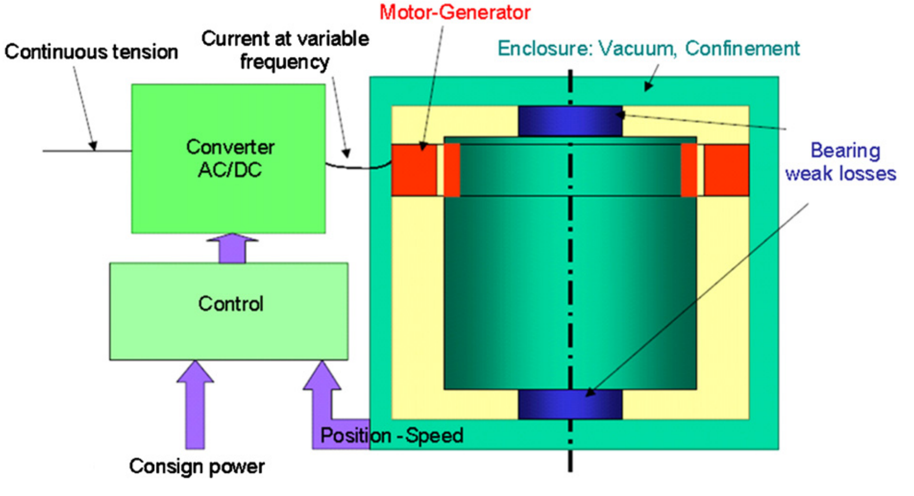


Fig. 14. Flywheel energy accumulators [16].

One advantage of this storage system is its great instantaneous efficiency, near 95% for a charge–discharge cycle [8]. Moreover, these systems are capable of discharging the near totality of the stored energy, as opposed to batteries. They are very useful for applications requiring continuous operation with a great number of complete charge–discharge cycles. The fast response time (under 100 ms) of these systems makes them ideal for regulating network stability (load levelling). Their major shortcoming is the refrigeration system which, while not a problem in itself is quite costly and makes operation more complicated.

Massive storage projects (5000–10,000 MWh) require very large coils (several 100 m in diameter) that generate enormous electromagnetic forces. They have to be installed underground to limit infrastructure costs.

4.11. Energy storage in supercapacitors

These components have both the characteristics of capacitors and electrochemical batteries, except that there is no chemical reaction, which greatly increases cycling capacity. Energy storage in supercapacitors is done in the form of an electric field between two electrodes. This is the same principle as capacitors except that the insulating material is replaced by electrolyte ionic conductor in which ion movement is made along a conducting electrode with a very large specific surface (carbon percolants grains or polymer conductors) [6].

The energy/volume obtained is superior to that of capacitors (5 Wh/kg or even 15 Wh/kg), at very high cost but with better discharge time constancy due to the slow displacement of ions in the electrolyte (power of 800–2000 W/kg). The direct consequence is that the maximum operational voltage is limited to a few volts per element (2.5–3 V, modules up to 1500 F). Serial connection, as opposed to capacitors, is required to reach normal voltages in power applications and form modules with 50–100 kW of storage capacity (Fig. 15).



Fig. 15. Supercapacitors assembled in series [1].

Supercapacitors generally are very durable, that is to say 8–10 years, 95% efficiency, and 5% per day self-discharge, which means that the stored energy must be used quickly.

5. Characteristics of energy storage techniques

Energy storage techniques can be classified according to these criteria:

- The type of application: permanent or portable.
- Storage duration: short or long term.
- Type of production: maximum power needed.

It is therefore necessary to analyze critically the fundamental characteristics (technical and economical) of storage systems in order to establish comparison criteria for selecting the best technology.

The main characteristics of storage systems on which the selection criteria are based are the following.

5.1. Storage capacity

This is the quantity of available energy in the storage system after charging. Discharge is often incomplete. For this reason, it is defined on the basis of total energy stored, W_{st} (Wh), which is superior to that actually retrieved (operational), noted W_{ut} (Wh). The usable energy, limited by the depth of discharge, represents the limit of discharge depth (minimum-charge state). In conditions of quick charge or discharge, the efficiency deteriorates and the retrievable energy can be much lower than storage capacity. On the other hand, selfdischarge is the attenuating factor under very slow regime (see Fig. 16).

5.2. Available power

This parameter determines the constitution and size of the motor-generator in the stored energy conversion chain. It is generally expressed as an average value, as well as a peak value often used to represent maximum power of charge or discharge, P_{max} (W).[1]

5.3. Depth of discharge or power transmission rate

Energy storage is a slow process that subsequently must quickly release energy on demand. The power output, or discharge, can be a limiting factor called the power transmission rate. This delivery rate determines the time needed to extract the stored energy. The power must be available for delivery during peak hours, that is to say the amount of energy used, if significant, is representative of a non-optimum system design, or a fundamental limit of the storage apparatus [18].

[1]Maximum power of charge and discharge are sometimes different.

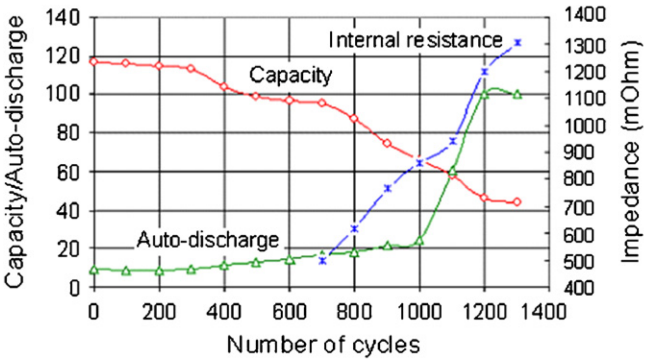


Fig. 16. Variation of energy capacity, self-discharge and internal resistance of a nickel–metal hydride battery (6V, 950 mA) with the number of cycles [17].

5.4. Discharge time

This is the maximum-power discharge duration, $\tau(s) = W_{st}/P_{max}$. It depends on the depth of discharge and operational conditions of the system, constant power or not. It is a characteristic of system adequacy for certain applications.

For example [19], for a pumped storage system, the storage capacity is dependent on the water mass and the height of the waterfall, while the maximum power is determined by the size of the conduits and the power of the reversible turbine–electrical-machine units.

The difficulty in separating the power and energy dimensions of the system makes it difficult to choose a optimum time constant for most storage technologies.

5.5. Efficiency

This is the ratio between released energy and stored energy, $\eta = W_{ut}/W_{st}$. This definition is often oversimplified because it is based on a single operation point [19]. Yet, systems have charging, no-load, and self-discharge losses. The definition of efficiency must therefore be based on one or more realistic cycles for a specific application. Instantaneous power is a defining factor of efficiency. For the storage system to be really competitive, it must have good overall efficiency. This means that, for optimum operation, the power-transfer chain must have limited losses in terms of energy transfer and self-discharge. This energy conservation measure is an essential element for daily network load-levelling applications (Fig. 16).

Fig. 17 illustrates in simplistic fashion the existence of an optimum discharge time and maximum efficiency [9].

For actual storage systems, these results are more complex since the elements of the illustration vary with the operation point, and notably with the state of charge (Fig. 18).

5.6. Durability (cycling capacity)

This refers to the number of times the storage unit can release the energy level it was designed for after each recharge, expressed as the maximum number of cycles N (one cycle corresponds to one charge and one discharge).

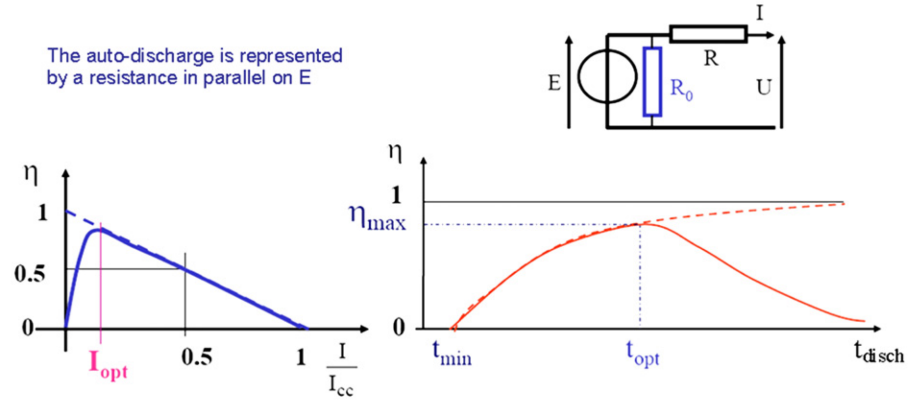


Fig. 17. Graphs representing the effect of current or time discharge, as well as the self-discharge effect on efficiency of electrochemical accumulator. The dotted lines correspond to a model with no self-discharge resistance (I: source of current, I_{CC}: short-circuit current) [20].

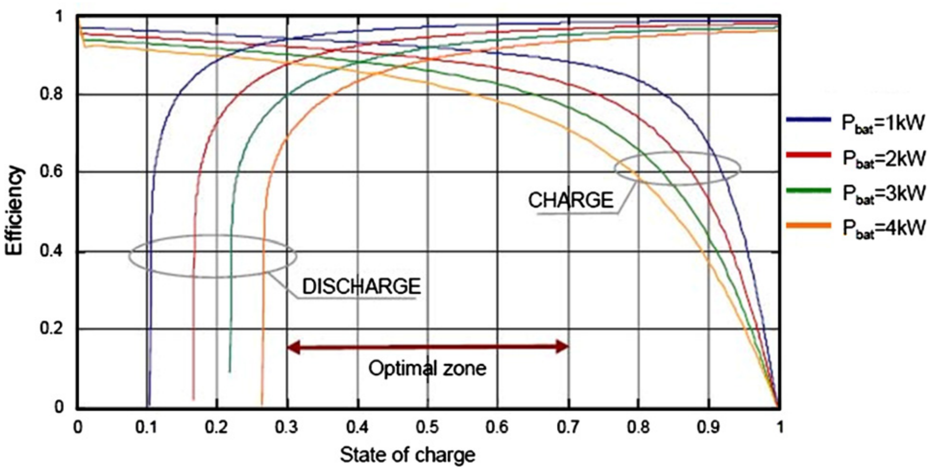


Fig. 18. Power efficiency of a 48 V-310 Ah (15 kWh/10 h discharge) lead battery [20].

All storage systems are subject to fatigue or wear by usage. This is usually the principal cause of aging, ahead of thermal degradation. The design of a storage system that considers the endurance of the unit in terms of cycles should be a primary importance when choosing a system. However, real fatigue processes are often complex and the cycling capacity is not always well defined. In all cases, it is strongly linked to the amplitude of the cycles (Fig. 19) and/or the average state of charge [21]. As well, the cycles generally vary greatly, meaning that the quantification of N is delicate and the values given represent orders of magnitude.

5.7. Autonomy

This refers to the maximum amount of time the system can continuously release energy. It is defined by the ratio between the energy capacity (restorable energy) and maximum

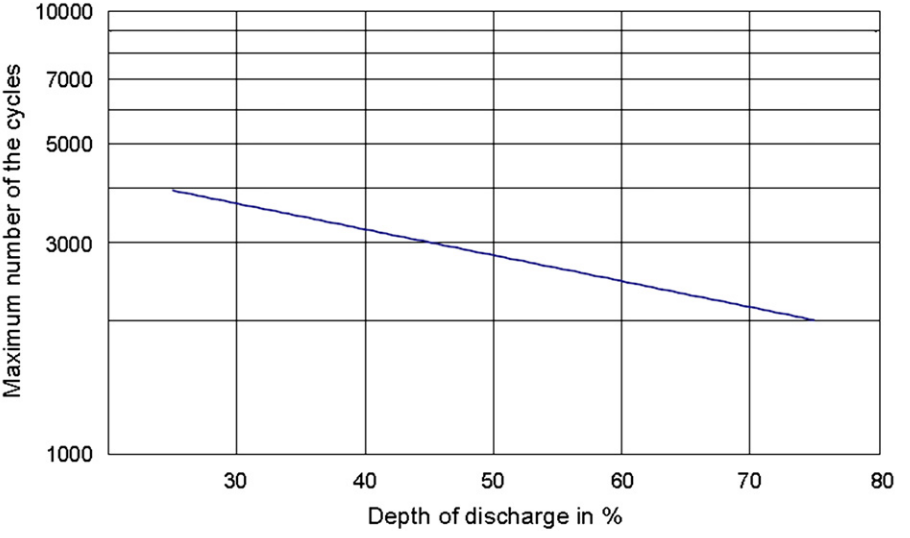


Fig. 19. Evolution of cycling capacity as a function of depth of discharge for a lead–acid battery [21].

discharge power, $a = W_{ut}/P_d$. The autonomy of a system depends on the type of storage and the type of application. For small systems (a few kWh) in an isolated area relying on intermittent renewable energy, autonomy is a crucial criterium.

5.8. Costs

Like any other investment, a storage system is an interesting venture when total gains exceed total expenses. The capital invested and operational costs (maintenance, energy lost during cycling, aging) are the most important factors to consider for the entire life of the system.

Low-efficiency systems with low cycling capacity generally require the lowest initial investment. It is therefore crucial to carry out an analysis of the estimated durability of the entire system, including the storage unit [9]. In terms of sustainable development, the overall costs over the entire life of the system, including materials, energy, and other environmental costs from fabrication to recycling, must be considered.

Generally, the investment costs of storage is factored out using the following formula:[2] $C = C_1 W_{ut} + C_2 P_d$. The operational costs, spread over the lifespan of the system, are supposed to be proportional to the investment costs (in the order of 40% of investment over 20 years for electricity production systems) [8], for a total cost of $C_t = (ac_1 + c_2)P_d$. Here a is the autonomy.

5.9. Feasibility and adaptation to the generating source

To be highly efficient, a storage system needs to be closely adapted to the type of application (low to mid power in isolated areas, network connection, etc.) and to the type

[2] C_1 (in \$/kWh), C_2 (in \$/kW) and P_d represent, respectively, the unit cost per total energy capacity, discharge power and nominal discharge power.

of production (permanent, portable, renewable, etc.) (Fig. 20) it is meant to support. It needs to be harmonized with the network.

5.10. Self-discharge

This is the portion of the energy that was initially stored and which has dissipated over a given amount of non-use time.

5.11. Mass and volume densities of energy

These represent the maximum amounts of energy accumulated per unit of mass or volume of the storage unit, and demonstrate the importance of mass and volume for certain applications (especially for mass density of energy in portable applications, but less so for permanent applications).

5.12. Monitoring and control equipment

This equipment, on both the quality and safety of storage levels, has repercussions on the accessibility and availability of the stored energy.

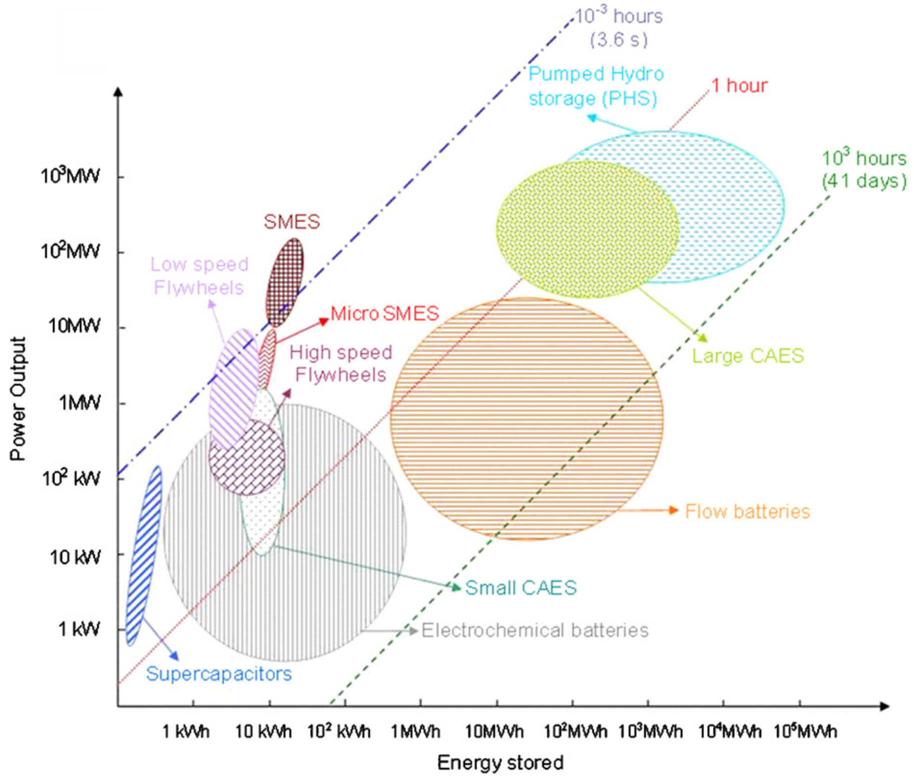


Fig. 20. Fields of application of the different storage techniques according to energy stored and power output [22].

5.13. Operational constraints

Especially related to safety (explosions, waste, bursting of a flywheel, etc.) or other operational conditions (temperature, pressure, etc.), they can influence the choice of a storage technology as a function of energy needs.

5.14. Reliability

Storage-system reliability is always an important factor because it is a guarantee of on-demand service [18].

5.15. Environmental aspect

While this parameter is not a criterium of storage-system capacity, the environmental aspect of the product (recyclable materials) is a strong sales pitch. For example, in Nordic countries (Sweden, Norway), a definite margin of the population prefers to pay more for energy than to continue polluting the country [1]. This is a dimension that must not, therefore, be overlooked.

5.16. Other characteristics

The ease of maintenance, simple design, operational flexibility (this is an important characteristic for the utility), fast response time for the release of stored energy, etc.

Finally, it is important to note that these characteristics apply to the overall storage system: storage units and power converters alike.

6. Comparison of the different storage techniques

To be able to compare the performance of the different storage techniques in the categories chosen, a list of criteria was previously analyzed, such as costs, density of energy, specific power, recyclability, durability, energy efficiency, etc. These criteria together allow to define a ‘‘performance index’’ for the four categories of application:

1. Low-power application in isolated areas, essentially to feed transducers and emergency terminals.
2. Medium-power application in isolated areas (individual electrical systems, town supply).
3. Network connection application with peak leveling.
4. Power-quality control applications.

To compare storage systems, Ragone’s diagram is generally used to represent performance in terms of the ratio of mass to energy and power [5]. This type of comparison is particularly interesting for portable units, for which mass is a critical aspect, but for permanent units, in a context of electrical-energy processing, life expectancy and total costs (investment, energy losses, and cycling fatigue) are the most important criteria.

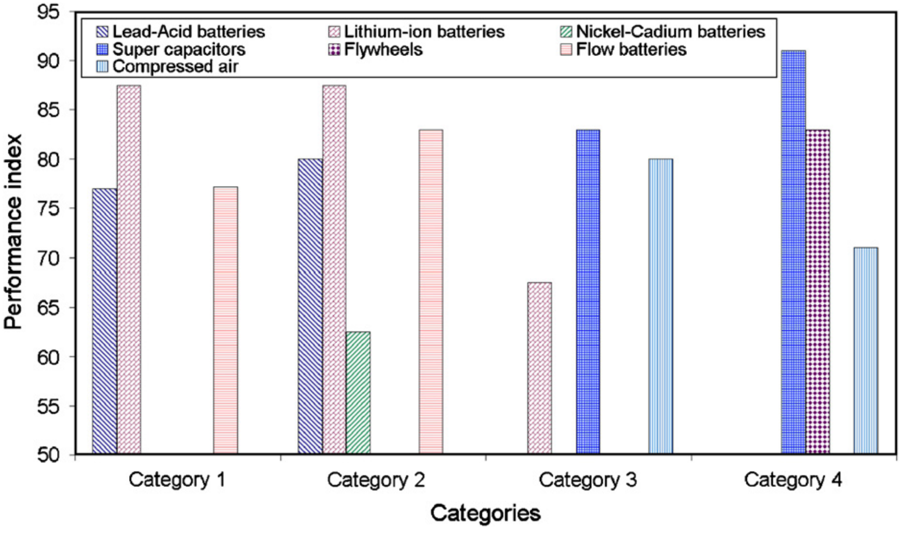


Fig. 21. Performance index for the nine storage technologies (except hydraulic and thermal) for the four categories of application [5].

The performance parameters of storage systems are often expressed for a wide variety of types and applications. The diagrams that follow show a comprehensible comparison of the different storage techniques. The comparison is based on the "performance index" defined as the applicability of the storage technique to the specified application taking into account the characteristics presented in Section 5. The data represents the typical systems in each category, but may not cover all available products (see Fig. 21).

6.1. Power comparison as a function of field of application

Large-scale, permanent energy storage applications can be classified into three main operational categories (Fig. 22):

- *Power quality required*: Stored energy, in these applications, is only used for a few seconds or less to ensure the quality of power delivered.
- *Buffer and emergency storage*: Stored energy, in these applications, is used for seconds to minutes to ensure service continuity when switching from one source of electricity to another.
- *Network management*: Storage systems, in these applications, are used to decouple synchronization between power generation and consumption. A typical application is load levelling, which implies storing up energy during off-peak hours (low energy cost) and the use of stored energy during peak hours (high energy cost).

6.2. Comparison of the energy efficiency (per cycle) of the storage systems

Energy efficiency and life expectancy (maximum number of cycles) are two important parameters to consider, among others, before choosing a storage technology, as they affect the overall storage costs. Low efficiency increases the effective energy costs since only

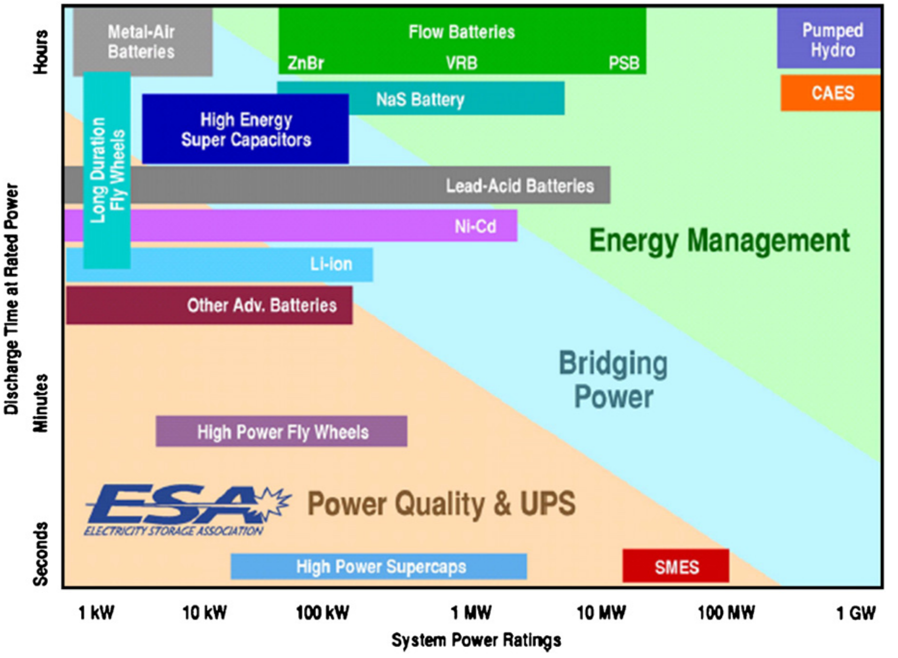


Fig. 22. Distribution of storage techniques as a function of their field of application [10].

a fraction of the stored energy can be used. A short lifespan also increases long-term costs as the storage unit needs to be replaced more often.

Actual expenses need to include the financial fees and operating expenses in order to develop a better idea of all the financial characteristics of a storage technique. In Fig. 23 are illustrated the characteristics of different storage techniques with respect to efficiency and lifetime.

6.3. Comparison of the investment cost

The investment cost associated to a type of storage is an important economical parameter and affect the total cost of energy production. Thus, some types of storage systems can only become profitable if a certain minimum of energy is supplied. The overall cost of the system then needs to be considered (including equipment durability and the cost of research) in order to achieve a complete cost analysis.

For example, despite the fact that lead–acid batteries are relatively inexpensive, they are not necessarily the least expensive option for energy management, due to their relatively low durability.

The cost of batteries in Fig. 24 was adjusted to exclude the cost of power electronics conversion. The cost of energy was also divided by the storage efficiency to obtain the cost per unit of useful energy. Installation costs also vary according to the type and size of the system [10].

Finally, it seems obvious that the various functions needed to design an energy storage system must be integrated into a coherent whole, adapted to the specifications, to reduce

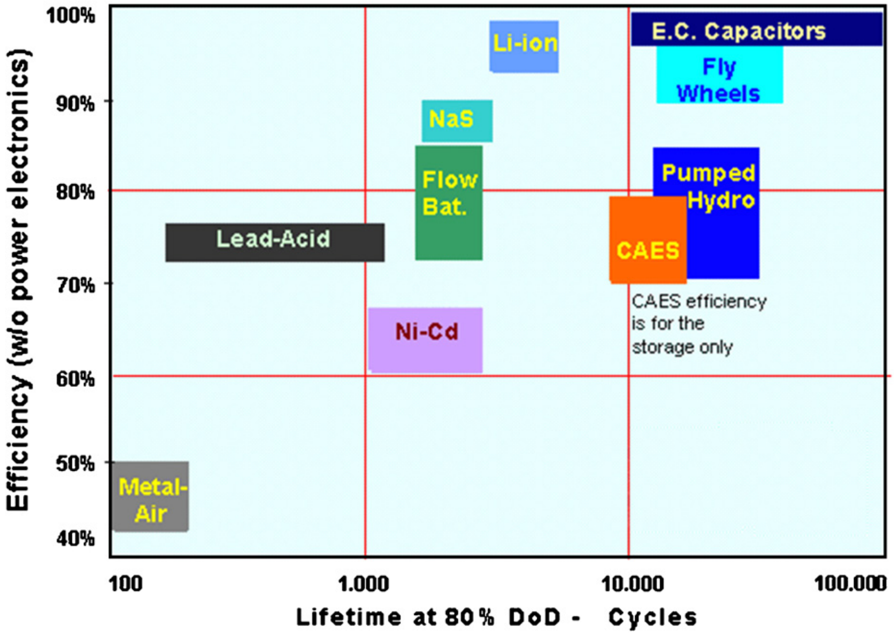


Fig. 23. Distribution of storage techniques as a function of energy efficiency and life expectancy [10].

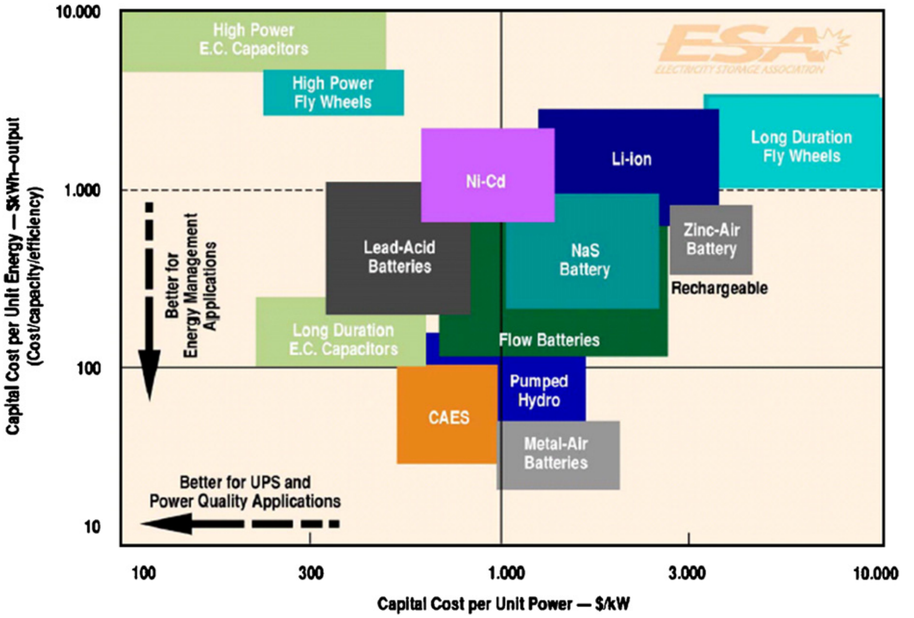


Fig. 24. Distribution of storage techniques as a function of investment costs per unit of power or unit of energy [10].

completion costs. This criterion is the main issue regarding the penetration of the system into the energy storage market.

6.4. Comparison of the investment cost per charge–discharge cycle

The cost per cycle could be the best way to evaluate the cost of an energy storage system designed for frequent charge–discharge applications.

Fig. 25 shows the principal component of this cost, taking into account durability and efficiency. For a more complete cost per cycle, research expenses as well as replacement and other costs, that remain unknown for emerging technologies, must be considered.

It should be noted that the cost per cycle is not an appropriate criterion for load levelling or energy arbitration, where the storage is less frequent and the energy costs are high and unstable [10].

6.5. Comparison based on mass or volume density

The different storage techniques can be classified as a function of the availability of energy and maximum power per liter (volume density) or per kilogram (mass density). This comparison is particularly important for the transmission industry, portable applications, and isolated sites (Fig. 26).

Mass is an important parameter for permanent applications in terms of material costs. One could therefore choose, for an electrical installation, a material with specific energy, but far from the maximum available (meaning that more material will be needed), at a unit cost that reduces the overall cost of the storage system. In this case, it is the price per kWh that is important, and not the kgs per kWh.

The volume of a storage system can be important, first of all if it has to be installed in a restricted or costly space, for example in urban areas. Another aspect of volume is its

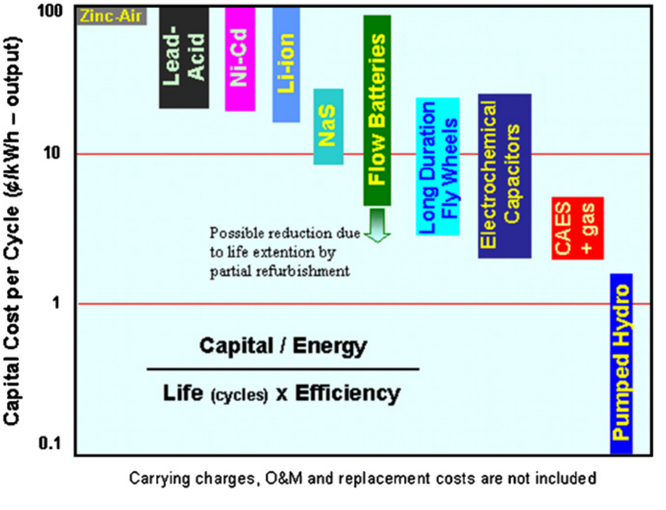


Fig. 25. Distribution of storage techniques as a function of investment costs calculated per charge–discharge cycle [10].

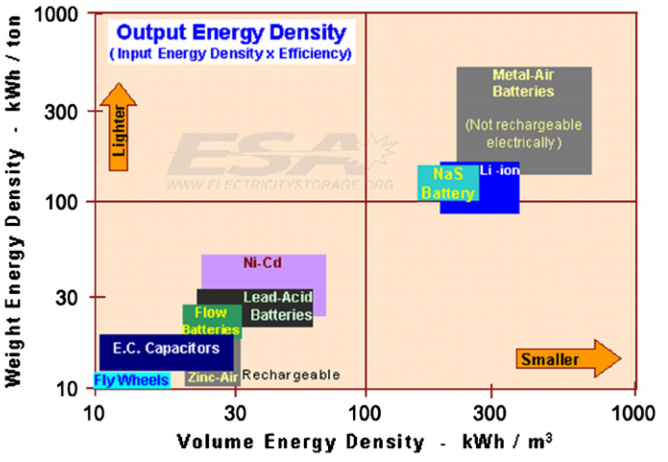


Fig. 26. Distribution of storage techniques as a function of their mass and volume densities of stored energy for small-scale applications [10].

incidence on the means and costs of containing and maintaining vacuum (flywheels for example) or cooling and thermal insulation systems. By increasing the volume, more material and a larger construction site are needed, thus increasing the overall cost of the system.

7. Overall analysis of the comparisons of energy storage techniques

As for low-power permanent applications, the key element is the lowest possible self-discharge. Based on the technical criteria alone, the lithium-ion unit is the best candidate.

As for small systems (a few kWh) in isolated areas relying on intermittent renewable energy, the key element is autonomy; the lead battery remains the best compromise between performance and cost. Lithium-ion has better performance but is still far too expensive.

For larger systems (a few 100 kWh), lead is still preferred, ahead of lithium, and the alternative solutions are either less efficient or too expensive: compressed air (self-discharge problems), fuel cells (expensive and low energy efficiency), and flow batteries (high maintenance costs).

In the third category, concerning peak-hour load levelling requiring high-energy storage (many MWh), compressed air and flow batteries are the best choices, with a definite cost advantage for the first of the two. But these technologies have not yet been tested in the field.

For the fourth category, concerning power quality, the key criteria are energy release capacity and cycling capacity. Here, flywheels and super-capacitors are better adapted than lithium-ion batteries.

Among the choices, lead batteries satisfy the technical criteria of all the categories, but have limited durability and are unreliable. Nickel-based and metal–air batteries do not meet any of the criteria selected (low performance, high cost). Fuel cells are for their part still a young technology. Finally, certain technologies are able to fulfill the needs of storage for intermittent energy supplies: hydraulic and thermal storage for large-scale

applications, and Superconducting Magnetic Energy Storage (SMES) for small-scale applications.

To answer to the future needs of delocalized production, energy storage will need to be technologically improved on the short to mid term. Lithium-ion batteries are very performant, but are much too expensive for application to systems in remote areas. The recycling and waste management of these batteries still need R&D work. Lead batteries are still the best cost-performance compromise, but are the weak link in an isolated system; their life expectancy needs to be improved if they are to better answer to the needs.

For network applications, the mid-term needs are ever growing: the most appropriate technologies (flow batteries, compressed air, super-capacitors, and flywheels) are more or less mature technologies and could be made more cost effective, more reliable, and more efficient.

8. Conclusions

The key element of this analysis is that it reviews the available energy storage techniques applicable to electrical power systems.

There is obviously a cost associated to storing energy, but we have seen that, in many cases, storage is already cost effective. More and more application possibilities will emerge as further research and development is made in the field [6].

Storage is a major issue with the increase of renewable but decentralized energy sources that penetrate power networks [23]. Not only is it a technical solution for network management, ensuring real-time load levelling, but it is also a mean of better utilizing renewable resources by avoiding load shedding in times of overproduction. Coupled with local renewable energy generation, decentralized storage could also improve power network sturdiness through a network of energy farms supplying a specific demand zone.

Many solutions are available to increase system security, but they are so different in terms of specifications that they are difficult to compare. This is why we tried to bring out a group of technical and economical characteristics which could help improve performance and cost estimates for storage systems.

Besides research work on the design and improvement of storage systems that are well adapted to the needs, it is also necessary to improve the life-expectancy evaluation models in terms of cycling capacity, and, sometimes, the efficiency models, as in the case of electrochemical accumulators.

Based on the contents of this study and carefully measuring the stakes, we find that:

1. The development of storage techniques requires the improvement and optimization of power electronics, often used in the transformation of electricity into storable energy, and vice versa.
2. The rate of penetration of renewable energy will require studies on the influence of the different storage options, especially those decentralized, on network sturdiness and overall infrastructure and energy production costs.
3. The study of complete systems (storage, associated transformation of electricity, power electronics, control systems, etc.) will lead to the optimization of the techniques in terms of cost, efficiency, reliability, maintenance, social and environmental impacts, etc.
4. It is important to assess the national interest for compressed gas storage techniques.

5. Investment in research and development on the possibility of combining several storage methods with a renewable energy source will lead to the optimization of the overall efficiency of the system and the reduction of greenhouse gases created by conventional gas-burning power plants.
6. Assessing the interest for high-temperature thermal storage systems, which have a huge advantage in terms of power delivery, will lead to the ability of safely establish them near power consumption areas.
7. The development of supercapacitors will lead to their integration into the different types of usage.
8. The development of low-cost, long-life flywheel storage systems will lead to increased potential, particularly for decentralized applications.
9. To increase the rate of penetration and use of hydrogen-Electrolyser fuel-cell storage systems, a concerted R&D effort will have to be made in this field.

Finally, despite the fact that we have not described in detail all the characteristics of the different storage techniques, we have shown that the possibility of storing electrical energy exists, whenever and wherever they are needed, and in any quantity.

Storage is the weakest link of the energy domain, but is a key element for the growth of renewable energies. When the energy source is intermittent and located in an isolated area which cannot be connected to the distribution network, storage becomes crucial. This need is not as obvious when the source of energy is connected to the network—as is the case for wind turbines and photovoltaic systems in industrialized countries—but storage could become unavoidable in the future. Indeed, with the opening of the energy market, many delocalized sources, usually intermittent renewable sources, will be connected to the network, which could lead to destabilization. To overcome this problem, storage and sound management of these resources are the best solutions.

Acknowledgments

The authors kindly acknowledge the financial support from Natural Sciences and Engineering Research Council (NSERC) and Fonds Québécois de Recherche sur la Nature et les Technologies (FQRNT) through research grants.

References

[1] Faure F. Suspension magnétique pour volant d'inertie. Thèse de doctorat. Institut National Polytechnique de Grenoble, France; Juin 2003.
[2] 〈www.mines-energie.org/Conferences〉.
[3] Rudell A. Storage and Fuel Cells. EPSRC SuperGen Workshop: Future Technologies for a Sustainable Electricity System. University of Cambridge; 2003.
[4] Mémoire concernant la contribution possible de la production éolienne en réponse à l'accroissement de la demande québecoise d'électricité d'ici 2010. Régie de l'énergie, Québec, Canada. Dossier R-3526; Avril 2004.
[5] Couffin P, Perrin M. Le stockage des énergies intermittentes. Commissariat à l'Énergie Atomique (CEA). Clefs CEA (50–51), hiver 2004–2005. p. 136–8. 〈www.cea.fr〉.
[6] Multon B, Ruer J. Stocker l'électricité: Oui, c'est indispensable, et c'est possible ! pourquoi, où, comment? Publication ECRIN en contribution au débat national sur l'énergie; Avril 2003.
[7] Ibrahim H, Ilinca A, Peroon J. Solutions de stockage de l'énergie éolienne. Rapport interne, UQAR, UQAC; Janvier 2006.

[8] Anzano JP, Jaud P, Madet D. Stockage de l'électricité dans le système de production électrique. Techniques de l'ingénieur, traité de Génie Électrique D4030; 1989.
[9] Multon B, Robin G, Erambert E, Ben Ahmed H. Stockage de l'énergie dans les applications stationnaires. Colloque Énergie électrique: besoins, enjeux, technologies et applications. Belfort, France, 18 juin 2004. pp. 64–77.
[10] ⟨www.electricitystorage.org⟩.
[11] Bradshaw DT, Ingram M. Pumped hydroelectric storage (PHS) and compressed air energy storage (CAES), IEEE PES summer meeting on energy storage, 2000.
[12] Robyns B. Contribution du stockage de l'énergie électrique à la participation au services système des éoliennes. Séminaire SRBE–SEE–L2EP ''Éolien et réseaux: enjeux,'' 22 mars 2005.
[13] ⟨http://www.caes.net/mcintosh.html⟩.
[14] Van den Bossche P, Vergels F, Van Mierlo J, Matheys J, Van Autenboer W. SUBAT: An assessment of sustainable battery technology. Journal of power sources 2006;162(2):913–9.
[15] Davies TS, Nouri H, Jefferson CM. Alternative approaches to wind energy conversion systems. Wind Eng 1995;19(5):265–71.
[16] Multon B, Bernard N, Kerzrého C, Ben Ahmed H, Cognar JY, Dclamare J, Faure F. Stockage électromécanique d'énergie. Club CRIN Énergie Alternatives – Groupe Stockage d'énergie. Présentation du 23 Mai 2002.
[17] Buchmann I, Choisir une batterie qui aura une longue durée de vie, Cadex Electronics Inc. Canada. ⟨http://www.buchmann.ca⟩.
[18] Bonneville JM. Stockage cinétique. Institut de Recherche de l'Hydro-Québec, Varennes, Québec, Canada. Rapport interne; février 1975.
[19] Robin G, Rullan M, Multon B, Ben Ahmaed H, Glorennec PY. Solutions de stockage de l'énergie pour les systèmes de production intermittente d'électricité renouvelable. 2004.
[20] Gergaud O. Modélisation énergétique et optimisation économique d'un système de production éolien et photovoltaïque couplé au réseau et associé à un accumulateur. Thèse de l'ENS de Cachan;décembre 2002.
[21] Messenger R, Ventre J. Photovoltaic systems engineering. Boca Raton, FL: CRC Press; 1999.
[22] Emerging Energy Storage Technologies in Europe. Rapport Frost & Sullivan; 2003.
[23] Multon B. L'énergie électrique: analyse des ressources et de la production. Journées section électrotechnique du club EEA. Paris, France, 28–29 janvier 1999. p. 8.